Buoyancy generated by the combustion processes in a fire causes the formation of a plume. Such a plume can transport mass and enthalpy from the fire into the lower or upper layer of a compartment. In the present implementation, we assume that both mass and enthalpy from the fire are deposited only into the upper layer. In addition the plume entrains mass from the lower layer and transports it into the upper layer. This yields a net enthalpy flux between the two layers. Actually, the flame and plume will generally radiate somewhat into the lower layer, at least if it is not diathermous. So our approximation causes the upper layer to be somewhat hotter, and the lower layer somewhat cooler than is the case, at least in a well developed fire. For normal fires and door jet fires, plume entrainment is implemented as part of the fire calculation detailed in section 3.1.

A fire generates energy at a rate $\dot{Q}$. Some fraction, χ_R, will exit the fire as radiation. The remainder, χ_C, will then be deposited in the layers as convective energy or heat additional fuel so that it pyrolyses. Defining this quantity $(c_p m_e (T_u - T_e))$ to be the convective heat release rate, we can use the work of McCaffrey [1] to estimate the mass flux from the fire into the upper layer. This correlation divides the flame/plume into three regions as shown below. This prescription agrees with the work of Cetegen et al. [2] in the intermittent regions but yields greater entrainment in the other two

$$\text{flaming}: \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.011 \left(\frac{z}{\dot{Q}^{2/5}} \right)^{0.566} \qquad 0.00 \leq \left(\frac{z}{\dot{Q}^{2/5}} \right) < 0.08$$

$$\text{intermittent}: \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.026 \left(\frac{z}{\dot{Q}^{2/5}} \right)^{0.909} \qquad 0.08 \leq \left(\frac{z}{\dot{Q}^{2/5}} \right) < 0.20$$

$$\text{plume}: \qquad \frac{\dot{m}_e}{\dot{Q}} = 0.124 \left(\frac{z}{\dot{Q}^{2/5}} \right)^{1.895} \qquad 0.20 \leq \left(\frac{z}{\dot{Q}^{2/5}} \right)$$

regions. This difference is particularly important for the initial fire since the upper layer is far removed from the fire.

McCaffrey's correlation is an extension of the common point source plume model, with a different set of coefficients for each region. These coefficients are experimental correlations, and are not based on theory. The theory appears only in the form of the fitted function. The binding to the point source plume model is for the value for Z where the mode changes, namely from flaming to intermittent to plume.

Within CFAST, the radiative fraction defaults to 0.30 [3]; i.e., 30 percent of the fires energy is released via radiation. For other fuels, the work or Tewarson [4], McCaffrey [5], or Koseki [6] is available for reference. These place the typical range for the radiative fraction from about 0.15 to 0.5.

In CFAST, there is a constraint on the quantity of gas which can be entrained by a plume arising from a fire. The constraint arises from the physical fact that a plume can rise only so high for a given size of a heat source. In the earlier versions of this model (FAST version 17 and earlier),

the plume was not treated as a separate zone. Rather we assumed that the upper layer was connected immediately to the fire by the plume. The implication is that the plume is formed instantaneously and stretches from the fire to the upper layer or ceiling. Consequently, early in a fire, when the energy flux was very small and the plume length very long, the entrainment was over predicted. This resulted in the interface falling more rapidly than was seen in experiments. Also the initial temperature was too low and the rate of rise too fast, whereas the asymptotic temperature was correct. The latter occurred when these early effects were no longer important.

The correct sequence of events is for a small fire to generate a plume which does not reach the ceiling or upper layer initially. The plume entrains enough cool gas to decrease the buoyancy to the point where it no longer rises. When there is sufficient energy present in the plume, it will penetrate the upper layer. The effect is two-fold: first, the interface will take longer to fall and second, the rate of rise of the upper layer temperature will not be as great. To this end the following prescription has been incorporated: for a given size fire, a limit is placed on the amount of mass which can be entrained, such that no more is entrained than would allow the plume to reach the layer interface. The result is that the interface falls at about the correct rate, although it starts a little too soon, and the upper layer temperature is over predicted, but follows experimental data after the initial phase (see sec. 5).

For the plume to be able to penetrate the inversion formed by a hot gas layer over a cooler gas layer, the density of the gas in the plume at the point of intersection must be less than the density of the gas in the upper layer. In practice, this places a maximum on the air entrained into the plume. From conservation of mass and enthalpy, we have

$$\dot{m}_p = \dot{m}_f + \dot{m}_e$$

$$\dot{m}_p c_p T_p = \dot{m}_f c_p T_f + \dot{m}_e c_p T_l$$

where the subscripts $p, f, e,$ and l refer to the plume, fire, entrained air, and lower layer, respectively. The criterion that the density in the plume region be lower than the upper layer implies that $T_u < T_p$. Solving eq (44) for T_p and eliminating $\dot{m}_p$ using eq (43) yields

$$T_p = \frac{T_f \dot{m}_f + T_l \dot{m}_e}{\dot{m}_f + \dot{m}_e} > T_u$$

or

$$\dot{m}_e < \left(\frac{T_f - T_u}{T_u - T_l} \right) \dot{m}_f \tag{4}$$

Assuming all of the convective energy released by the fire goes into the upper layer, the net increase in temperature in the upper layer is

$$\dot{Q}_c(fire) = \dot{m}_f c_p(T_f - T_u)$$ (5)

Substituting eq. (47) into eq. (46) yields the final form of the entrainment limit used in the CFAST model:

$$\dot{m}_e < \frac{\dot{Q}_c(fire)}{c_p(T_u - T_l)}$$ (6)

which is incorporated into the model. It should be noted that both the plume and layers are assumed to be well mixed with negligible mixing and transport time for the plume and layers.

[1]   McCaffrey, B. J., "Momentum Implications for Buoyant Diffusion Flames," *Combustion and Flame 52,* 1983, p. 149.

[2]   Cetegen, B. M., "Entrainment and Flame Geometry of Fire Plumes," Ph.D. Thesis, California Institute of Technology, Pasadena 1982.

[3]   Drysdale, D., "An Introduction to Fire Dynamics," John Wiley and Sons, New York, 143 p. (1985).

[4]   Tewarson, A., Combustion of Methanol in a Horizontal Pool Configuraiton, Factory Mutual Research Corp., Norwood, MA, Report No. RC78-TP-55 (1978).

[5]   McCaffrey, B. J., Entrainment and Heat Flux of Bouyant Diffusion Flames, Natl. Bur. Stand. (U. S.), NBSIR 82-2473, 35 p. (1982).

[6]   Koseki, H., Combustion Properties of Large Liquid Pool Fires, Fire Technology, **25(3)**, 241-255 (1989).